TEMPERATURE VARIATIONS ALONG A FORESTED SLOPE IN THE BENT CREEK EXPERIMENTAL FOREST, N.C.

By LELAND T. PIERCE

[Weather Bureau Office, Asheville, N.C., January 1934]

Beginning with October 1932, a project has been operated in the Bent Creek Experimental Forest, near Asheville, N.C., of the Appalachian Forest Experiment Station to determine the temperature characteristics responsible for a noticeable differential between the leafing times of trees at different levels in the Bent Creek Valley. A retardation of as much as 2 weeks has been observed in the lower half of the valley which could be accounted for only by the accumulation therein of cold air as in frost pockets. The purpose of this project was to measure existing differences in temperature, and possibly to arrive at conclusions which might be applicable to other valleys and coves similarly situated.

The temperature distribution in the Bent Creek Valley is closely related to the temperature distributions in the mountain regions studied by Prof. H. J. Cox in 1913–16 in connection with "Thermal Belts." [1] The appearance of the Bent Valley at leafing time suggests a small-scale thermal belt, but it is now certain that the phenomenon is due instead to the submergence of this smaller valley in the general inversion of the larger valley into which it opens, a condition common in mountainous regions.

Bent Creek is a tributary flowing into the French Broad River at an approximate elevation above sea level of 2,000 feet about 7 miles upriver from Asheville, N.C. In this vicinity the French Broad Valley is several miles wide, and makes up, with its tributaries, a broad interior depression sometimes known as the "Asheville Plateau." The experimental forest, a tract of some 1,100 acres, lies within the Bent Creek Valley which has a NNE.–SSW. axis and opens toward the north. The valley is almost completely forested with mixed hardwoods, there being only two small cleared areas, one at the mouth, the other extending on the eastern side over the top of Glenn Bald. For the most part, the slopes on either side are very irregular, facing in various directions, but one long, continuous slope leads northwestward down from Glen Bald at 2,692 feet elevation to the creek bottom at 2,100 feet. Along this slope the weather stations were installed late in September 1932.

Three stations were established. The base station was placed at 2,100 feet above sea level, near the creek bottom; the other two at elevation intervals of 200 feet were located at 2,300 and 2,500 feet, respectively. These were all on a regular slope and under a forest cover which has as nearly a uniform crown density as is ordinarily possible to find. Each was equipped with maximum and minimum thermometers, Weather Bureau type hygrothermograph and soil thermometers. The hygrothermographs were checked weekly with a sling psychrometer and it is believed that to an acceptable degree of accuracy these three stations recorded temperatures and humidities accounted for purely by differences in elevation and position in the valley. Credit for this work belongs to Mr. E. M. Manchester, resident manager at the experimental forest, who tended the station equipment.

In the measurement of inversion temperatures in a valley it is customary to place the weather stations in the open. However, these stations were placed under forest cover and therefore the results undoubtedly are somewhat different from those which would have been obtained in the open. In particular the unexpected frequency of large inversions here found may be accounted for in part by the fact that the stations were placed under forest cover since trees interfere with atmospheric circulation and thereby favor stratification of the air, a condition essential to inversion.

THERMAL CONDITIONS IN A MOUNTAINOUS REGION

To understand more thoroughly the reasons for the results obtained, it is well to explain briefly the thermal characteristics of a mountainous region. There temperatures vary greatly from place to place and from elevation to elevation principally on account of air drainage.

The surface of the earth continuously loses heat by radiation, and therefore on still clear nights ground surfaces become cool and in turn correspondingly chill the adjacent air. This cold air drains down the mountain sides, flowing water-like into the valleys below where it is further cooled by radiation. Thus the valleys become filled with "lakes" or "rivers" of dense, cold air tending always to drain out wherever possible into regions of lower elevation. The more gentle the slope the more sluggish the drainage, and vice versa. In this section most valleys have gentle slopes and on still, clear nights so fill with cold air as completely to submerge therein the tributary coves and glens. As this drainage process continues during the night, the level of maximum temperature, marking the top of the inversion layer, creeps gradually up the sides of the valleys, and finally reaches its greatest height at the time of the minimum temperature. This usually occurs when the rising sun puts an end to the net heat loss. The maximum height attained by the upper limit of the inversion layer, because it is reached at the time of lowest temperature, marks the elevation of the thermal belt in that particular valley.

In this section where the popular mind has been focused upon that phenomenon by Professor Cox's work, there is a good deal of misconception regarding the nature, and especially the level, of the thermal belt. Casual thought in the light of processes involved leads to the conclusion that there must be a definite range of elevation in a mountainous region within which the thermal belt will always be found. However, such is not the case. Rather than occurring at a definite elevation above sea level, the belt of highest minima is to be found at a specific height above the floor of each individual valley which displays the phenomenon at all. Indeed, not every valley has a thermal belt since topographic conditions must be favorable for the development of this condition. During a night of free radiation the valley fills up with cold air, presumably at a more or less definite rate, reaching its greatest depth at the time of the minimum temperature. In individual cases the height which will be reached by sunrise depends upon the length of the night, rate of radiation, cloudiness, and wind velocity as well as upon the local topographic conditions which allow for or prevent a normal filling up of the depression.

In a mountainous region such as the Southern Appalachians, the majority of valleys and coves cannot boast a thermal belt, simply because they are not deep enough. Each may have its own inversion, but the depth of the inversion layers as governed by topography, is so great that the valley is completely filled by drainage from higher land. In this case the level of the highest minima

[1] Cox, Henry J. Thermal belts and fruit growing in North Carolina. MO. WEA. REV. SUPPLEMENT NO. 19, Washington, 1923.

will be at, or well above, the ridge on either side. This is the state of affairs in the Bent Creek Valley, a tributary with higher mountains on all sides. The places of minor inversions, such as tributary valleys, submerged in the main valley inversion, often are called frost pockets. It might be better, however, to call these frost coves and restrict the name "pocket" to a place of little or no outlet.

In this connection it should be mentioned that the depth of the inversion layer is not the same on every inversion night. A reduction in the length of time during which free radiation goes on, as occasioned by cloudiness part of the night, or by a reduction in the normal rate of heat loss due to the presence of a smoke or haze layer, or partial cloudiness, will prevent its reaching the normal maximum depth. Many cases of this have been recorded at Bent Creek. Table 2 indicates the frequency of this condition as the number of nights on which the temperature was highest at the 2,300-foot level. In these cases it may be assumed that the belt of highest minimum is higher or lower than this level when the minimum is found at the elevation of 2,100 or 2,500 feet of the bottom or top, respectively.

An inversion of temperature is the rule in a mountainous section like this, occurring much more frequently than the reverse, which is normal for the free air. Nights of "norm" conditions are so much in the minority that average temperatures for a month or longer period invariably indicate a substantial inversion. Diurnal curves of mean seasonal temperatures in figure 1 bring out this fact.

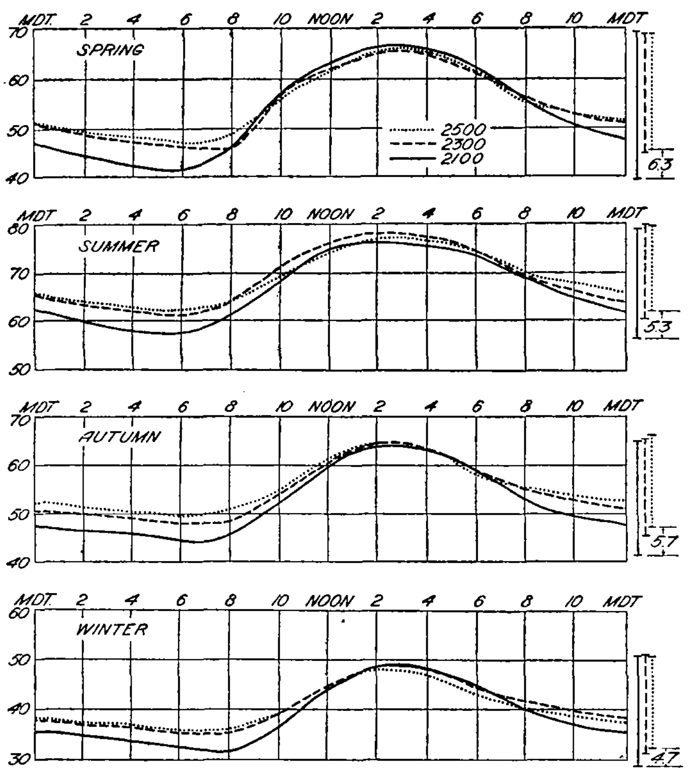

FIGURE 1.—Average diurnal march in temperature each season for the three stations.

AVERAGE SEASONAL TEMPERATURE CONDITIONS

Figure 1 shows graphically the diurnal variations in seasonal average temperatures for the three elevations. As is to be expected, the diurnal curves for all seasons are very similar, though the greatest variations are seen in the transitional seasons. Temperatures are lowest, for the most part, at the 2,100-foot level. This condition extends throughout the entire 24 hours, with the exception of mid-afternoon, during the period January to May, inclusive. This probably is due to the northwestern exposure, the bottom station being slightly more sheltered than those higher up. The highest maxima during the remainder of the year occurred about as frequently at the 2,300-foot as at the 2,500-foot elevation.

The 2,100-foot curve is most widely separated from the other two during the early morning hours but the increase

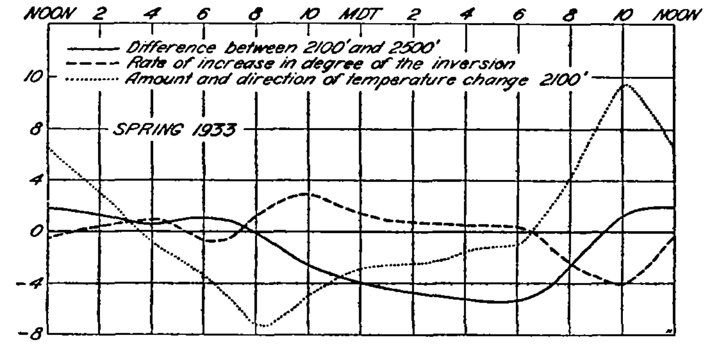

FIGURE 2.—Average diurnal difference in temperature between 2,100 and 2,500 feet, and rate of change at 2,100 feet—spring of 1933.

in departure after midnight is relatively small. This shows that the process of air drainage is most active before midnight, though the inversion slowly grows in intensity until sunrise. Figure 2, representing spring conditions, illustrates the rate of temperature fall at the 2,100-foot station, and also the steady growth of the inversion. The broken line indicates the rate of increase in temperature spread between the levels of 2,100 and 2,500 feet. The greatest 2-hourly changes appear between 8 p.m. and 10 p.m., the increase gradually tapering off from then until sunrise when the trend is reversed.

The ranges in temperature at all stations are greatest in spring and least in summer as might be expected from the transitional nature of the spring season and the rather settled conditions in summer. Also, the greatest inversions were recorded in spring and fall. This agrees with the findings of Professor Cox, but it is difficult to assign a specific reason for it other than that in these seasons there are fewer nights of norm conditions.

Table 1 brings out the feature of highest maxima temperatures at the bottom station during the 5-month period beginning with January, mentioned above. This situation presumably is owing largely to the absence of foliage on the overhanging trees during the winter and spring months which allows the sunshine to reach the surface in largest amount. The lowest minima, of course, always were recorded at the lowest station. The average temperature difference between this and the 2,500-foot level was least in winter and greatest in spring for reasons to be presented later.

Considering the average temperature level, as influenced partially by variations in the extremes, it can be said that the coldest part of the Bent Creek Valley is the bottom, and the warmest is at the higher elevations. The average annual temperature for the 2,500-foot level was 56.2° and at the 2,300-foot level, 55.7°, while at 2,100 feet it was only 53.7°, or 2.5° lower than at 2,500 feet. Assuming the thermal belt to be at or above 3,000 feet, as Professor Cox found, and as appears to be true from the success with orchards at these higher elevations, there is probably as much as 3.5° or 4° difference between the average temperature at the valley bottom and at Manning

Top, the head of this valley, which rises to 3,057 feet. It is conceivable that the growth of vegetation would for this reason be most rapid in the higher portions of the valley. Indeed, observation bears this out though the most noticeable differential is caused by the later occurrence of freezing temperatures in lower portions of the valley.

EFFECT OF CLOUDINESS ON INVERSIONS

The foregoing discussions have dealt almost entirely with average conditions which are truly significant. However, the most important differences in temperature can be seen from a consideration of representative examples. Naturally, the inversion condition is best developed on clear nights but this does not mean that cloudy nights are free from them. The first week in March offered an excellent example of a direct comparison between conditions on typically clear and cloudy nights. On March 3 and 4 the sky was overcast with strato-cumulus clouds and there was a gentle breeze, while the nights of March 5 and 6 were clear with light winds. Figure 3 shows graphically the temperature

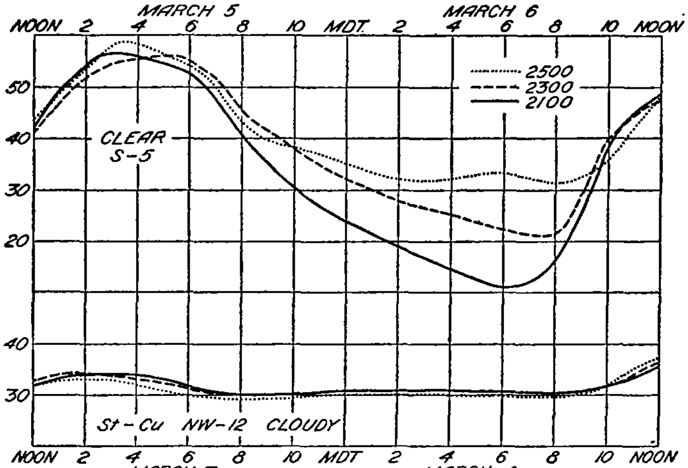

FIGURE 3.—Temperature march on characteristic clear and cloudy nights. (March 3-4, 1933, cloudy; March 5-6, 1933, clear.)

march from noon to noon covering those 2 nights. On the clear night there was an inversion amounting at 6 a.m. to 22°, this being the greatest for the entire year. The greatest difference between the two outside levels on the cloudy night was 1°. These instances represent the extreme condition, but they show the tendency for cloudiness and wind to prevent inversions.

TABLE 1.—*Average monthly maximum, minimum, and mean temperatures*

Elevation (feet)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Maxima:													
2,500	53.7	47.6	57.9	67.8	78.0	81.3	79.3	77.3	*78.4*	*65.7*	*53.5*	50.4	----
2,300	54.1	48.1	57.2	67.5	78.6	*81.5*	*80.3*	*77.4*	78.3	65.0	53.1	*51.0*	----
2,100	*54.6*	*48.8*	*58.1*	*68.7*	*79.6*	79.8	78.2	76.3	77.3	65.5	52.4	50.5	----
Minima:													
2,500	35.2	27.4	35.3	43.5	55.8	60.4	61.7	63.2	61.8	46.8	33.2	34.4	----
2,300	34.0	27.6	34.7	43.0	54.7	58.8	60.9	61.2	59.4	44.8	32.6	34.0	----
2,100	*29.2*	*24.2*	*29.6*	*35.8*	*50.5*	*52.4*	*58.0*	*59.2*	*56.0*	*40.8*	*28.1*	*30.5*	----
Means:													
2,500	*44.4*	37.5	*46.6*	*55.6*	*66.9*	*70.8*	70.5	*70.2*	*70.1*	*56.2*	*43.4*	42.4	56.2
2,300	44.0	*37.8*	46.0	55.2	66.6	70.2	*70.6*	69.3	68.8	54.9	42.8	*42.5*	55.7
2,100	41.9	36.5	43.5	55.2	65.0	66.1	68.1	67.8	66.6	53.2	40.2	40.5	53.7

Italic figures indicate maxima and mean highest.
Italic figures indicate minima lowest.

Twelve selected clear and cloudy nights in spring and summer were studied for the purpose of determining the average effect of cloudiness upon temperature inversions. In order to isolate the cloudiness factor care was exercised to choose nights having approximately the same wind, and to avoid nights with rainfall. A direct comparison was made on the basis of degree of inversion and significant results were obtained. On the clear nights the average maximum inversion recorded at 6 a.m. was 14°, and on the cloudy nights, 5.2°, or less than half that on clear nights. Radiation goes on at all times, clear or cloudy, but a cloud blanket ratains large amounts of heat which otherwise would have been lost to space. Another characteristic effect of cloudiness is that it slows down the rate of development of the inversion. On the clear nights the maximum inversion of 14° was only 1.3° greater than that at midnight. On the cloudy nights the 5.2° inversion at 6 a.m. was 1.7° greater than the midnight value, despite the fact that the total inversion was considerably smaller.

Mention has been made of the fact that, when considering average seasonal temperature marches in night temperatures, a marked inversion is shown. The degree of average inversion will be increased with an increasing frequency of clear nights and decreased by the inclusion of more nights of norm conditions. It is probable that the seasonal variations in the degree of average inversion, then, is largely a function of the frequency of norm conditions. In the year of this study, 1932–33, which may be considered fairly representative of other years, their frequency was greatest in winter with 20, and least in spring with 7, as brought out in table 2. Another factor causing a small winter average inversion is the relative frequency of large inversions. In winter there were 70 nights of inversion, 19 of which exceeded 10°, as against 85 and 25 instances of the same for the spring season. The combination of these two influences tends to make for relatively small average inversions in winter and summer as contrasted with the transitional seasons. Professor Cox obtained the same results in his study in the Carolina mountains, and he made the further observation that the largest individual inversions were recorded in spring and autumn. This is also in accord with findings at Bent Creek, but as yet no satisfactory physical explanation has been found.

TABLE 2

	Clear nights	Total inversion	Average inversion	Inversion, 10°+	Days maximum at 2,300	Norms
January	10	25	8.2	8	6	5
February	10	21	5.8	4	6	7
March	14	27	7.3	7	9	4
April	13	29	8.4	14	5	1
May	15	29	6.1	4	6	2
June	19	28	7.2	11	2	2
July	12	27	4.5	3	2	4
August	9	27	4.7	1	0	3
September	12	23	8.1	7	1	6
October	14	25	7.7	7	3	3
November	15	26	6.5	7	10	3
December	6	24	6.9	7	12	8
Spring	42	85	7.3	25	20	7
Summer	40	82	5.5	15	4	9
Autumn	41	74	7.4	21	14	12
Winter	26	70	7.0	19	24	20

CHARACTERISTICS OF DIURNAL TEMPERATURE VARIATIONS

Each distinct weather type has its own characteristic form of vertical temperature distribution in a valley such as Bent Creek. Figure 4 presents these different types. Three nights were selected from the April records, 1 of which the sky was clear, 1 cloudy, and 1 on which rain fell for the greater part of the night. There was a typical large inversion on the clear night, a smaller, shallower one on the cloudy night, and the rainy night was characterized by approximately norm conditions. The gradient on the cloudy night suggests the presence of a distinct thermal belt between the 2,300- and the 2,500-foot levels since there is an inversion below the lower of these and no further increase at the upper. It is probable that with the slower rate of heat loss by radiation, the depth of the inversion layer did not become great enough to fill the valley completely. A condition of this nature is relatively infrequent, as seen in table 2, though it occurred 10 times in November and 12 in December. These two were unusually cloudy months, and indeed this form of temperature distribution is invariably associated with night cloudiness. It represents a partially developed inversion.

The characteristics of the three station sites are well brought out by comparing the rates of temperature change throughout the 24-hour period. These values are given in figure 5 for the spring season. The three stations, situated as they are on a uniform northwest slope, receive sunshine in the morning at almost the same time, and therefore show simultaneous recovery from the minimum. However, the rate of rise is much greater at the 2,100-foot station than it is higher up the slope. This, of course, is due to the rapid dissipation of the inversion. Sixteen selected inversion mornings showed a lag in time of recovery averaging 45 minutes behind the time of sunrise. This lag probably represents the time required for the sun to rise high enough in the heavens to shine down this particular slope. In the evening, between 6 and 8 o'clock, a pronounced dip occurs in the 2,100-foot station curve, bringing it well below those for the 2,300-foot and the 2,500-foot stations. This indicates an early beginning of inversion conditions at the lower levels as occasioned by the bottom station being enveloped in the shadow of the western valley wall while sunshine is still being received at the upper stations. This early start in the formation of the inversion is, of course, characteristic of valleys having a north-south axis, and must be absent from those opening

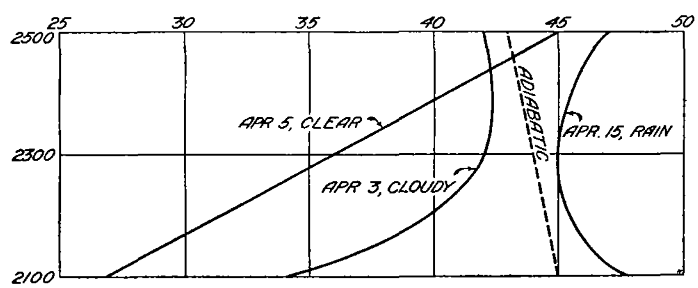

FIGURE 4.—Characteristic weather types on three April nights.

toward the west or southwest. Considerations such as these tend to emphasize the extreme complexity of temperature conditions in a mountainous country.

TOTAL RADIATIONAL COOLING

In arriving at the actual amount of radiational cooling which takes place by virtue of valley conditions, one cannot depend entirely upon the recorded temperature differences. Cold air draining down the mountain side undergoes dynamical heating with its descent at the rate of approximately 1° for each 200 feet drop. Allowing, then, for a 2° heating of air which flowed down from the 2,500-foot to the 2,100-foot level, the total radiational cooling at the valley bottom is 2° greater than the actual difference recorded. For instance, on March 6, when the actual temperature difference was 22°, the total cooling was 24°. Considered from this standpoint, the average seasonal cooling due to radiation becomes 9.3° for spring, 7.5° for summer, 9.4° for autumn, and 9° for winter months.

Professor Cox advanced the idea that air drainage does not proceed down the slope continuously, but rather in spurts. This was based upon the observed irregularity of downward night-temperature curves at slope stations. As a mass of cold air flows down the slope, the dynamically heated air actually raises the temperature at a station in its path for a short time before it has been cooled down to the temperature of the air formerly at that point. In this study the same feature is evident. At both the 2,500-foot and the 2,300-foot stations the downward trend of the temperature curves is almost invariably broken by

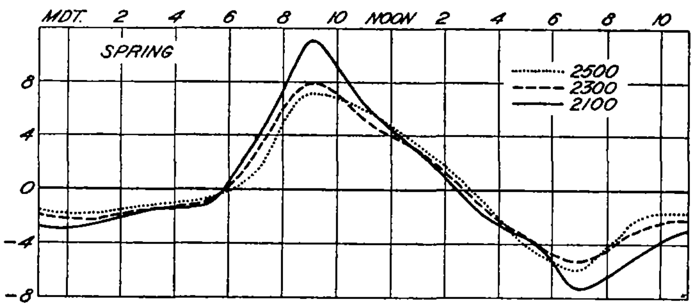

FIGURE 5.—Amount and direction of 2-hourly temperature changes, spring of 1933.

momentary rises, while this feature is not in the least apparent at the bottom station where the air has stagnated.

ISOPLETH CHARTS

One of the most convenient and readily understandable methods of representing graphically the temperature changes taking place throughout the day at different elevations is by use of the isopleth chart. By this means the rate of temperature change, the direction of the gradient at any particular time and the amount of difference between different levels can quickly be observed. Such charts have been prepared for average conditions, and also for the 10 nights of greatest inversion in each season. The spring set is presented as a means for making clearer the changes which took place in this valley. The rapid development of the inversion is clearly shown by the horizontal density of the lines, and the steepness of the vertical temperature gradient is shown by their vertical density. The average sunrise and sunset times are indicated by the heavy double lines. It is probable that the growth of the inversion is a continuous process, the level of maximum temperature being gradually lifted as the valley fills with cold air. The dotted lines represent the progress of this process. The quickness with which this warm layer reaches the top station is in itself a good indication that the height of the thermal belt is considerably above the 2,500-foot elevation, and that this phenomenon does not take place within the confines of the valley. The rapid dissipation of the inversion after sunrise is especially noticeable.

It is evident from the data collected in this study that the lower portion of the Bent Creek Valley, in which the leafing of trees is materially retarded, constitutes a sort of frost pocket within a much larger basin, and which, because of its relatively small size, has no true thermal belt of its own, such as occurs along the walls of the including, greater valley at an elevation of approximately 3,000 feet above sea level.

Obviously the conditions in Bent Creek Valley are common to all like valleys and coves in the mountainous region whose floors have a gentle slope, and are dominated by a larger valley system. Coves on steeply sloping mountain sides are not frost pockets since cold air drains out as fast as it accumulates. The direction in which the valley extends undoubtedly has a direct bearing upon the diurnal changes; inversions probably develop more quickly in those having a north-south axis than in those opening toward the western sun. Variations in the extent of inversions in mountain valleys and coves, and in the rates of their formation and dispersal are well-nigh infinite.

This study is far from exhaustive, even for this particular valley, but it serves to throw light upon the changes in temperature which take place in similar valleys. If stations had been located in different portions of this valley they undoubtedly would have yielded slightly different results, but it is certain that those differences would have been quantitative rather than qualitative.

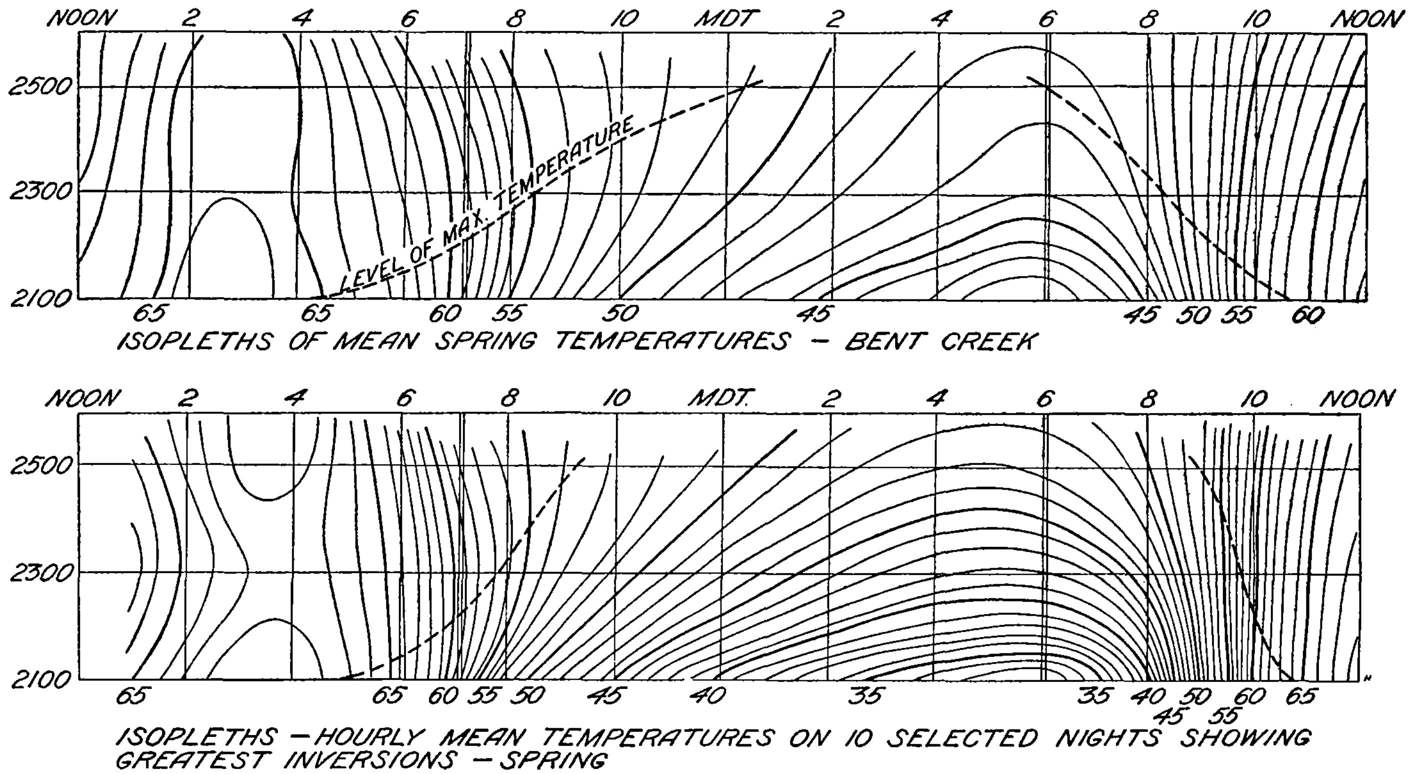

FIGURE 6.—Upper: Isopleths of mean spring temperatures, Bent Creek. Lower: Isopleths, hourly mean temperatures on 10 selected nights showing greatest inversions—spring.

THE GREAT DUSTSTORM OF NOVEMBER 12, 1933

By M. R. HOVDE

[Weather Bureau Office, Huron, S.Dak.]

In the climatological reports of the Great Plains will be found many accounts of severe dust and sandstorms. The MONTHLY WEATHER REVIEW has published narratives and articles concerning the outstanding storms of this nature. The duration and severity of duststorms depend on (1) the type of storm; (2) the covering of the soil, whether bare or vegetated; (3) the rainfall preceding the storm, or water content of the surface.

The whirlwind type (thunderstorms, tornadoes, and whirlwinds) may cause duststorms over limited areas only and their duration is short, in keeping with the characteristics of these local disturbances.

In the shift-wind type one refers to the area of low pressure with a characteristic trough and wind-shift line. In nature's effort to restore equilibrium, winds of gale force may raise dust along the wind-shift line.

The third type may be called the straight-wind type. Such a type calls for an area of high pressure and steep barometric gradient, which occurs only near the forward border of such area.

In the great duststorm of Sunday, November 12, 1933, the third or straight-wind type prevailed. This duststorm probably covered the greatest area of recent sandstorms, involving the vast territory from the Canadian line—Lake Superior to Montana—southward to the western Ohio and lower Missouri Valleys, a region of greater extent than the combined areas of France, Italy, and Hungary. Over South Dakota the dirtstorm was the severest within the memory of old settlers and cooperative observers. In adjoining States the prevalence of dust varied according to surface protection by vegetation or recent precipitation. The northern portions of Minnesota and North Dakota had a light snow layer and during the storm received precipitation which reduced the dust annoyance to a great extent. In Iowa the high winds blew much corn from the stalks, visibility was low and artificial lights were required during the day. Flying schedules on the airways into the Dakotas and Manitoba, Canada, were canceled.

The morning map of the 11th revealed a disturbance moving rapidly southeastward over Alberta, Fairview, 29.60 inches, and the anticyclone was centered at Boise, Idaho, 30.54 inches. On the morning of the 12th the Alberta storm reached southern Manitoba, Canada,